Chapter 8
Performance

8-1. General

This chapter discusses the performance of RCC dams and similar RCC structures with respect to watertightness and seepage control measures, joints and cracking, resistance to abrasion-erosion and freezing and thawing, and other effects such as sulfate attack or alkali-aggregate reaction. Strength and other properties of completed RCC structures are addressed in Chapter 4, Properties, and are not discussed in this chapter. Additional information on performance is contained in ACI 207.1R and ACI 207.5R. Since the construction of Willow Creek Dam in Oregon in 1982, over 26 RCC dams had been constructed in the United States, and over 161 RCC dams had been constructed worldwide, by 1994. In spite of the large number of RCC dams constructed worldwide, over 90 percent have been constructed since 1986. Hence, information on long-term performance has yet to be documented. Although this is a relatively short performance record, there are some performance lessons from the structures currently in service. The overall performance to date for RCC dams has been equivalent to conventional concrete dams in all respects.

8-2. Watertightness and Seepage Control Measures

RCC dams have had an overall good performance record for watertightness. Several cases have received a significant amount of attention (notably Willow Creek Dam (Schrader 1988)) for the seepage observed on the downstream face upon first filling. This section covers the reported seepage performance of RCC dams, including the effects of the RCC mixture on seepage, special treatments to reduce seepage, the use of geomembranes, and the use of waterstops and drains. Seepage is generally measured in dams by weirs at key points, or it is measured from collection pipes. Although seepage has been observed on a number of RCC dams, foundation seepage (such as from foundation drains) and seepage through the dam body (generally from joint and other interior dam drains) are often mixed and have not been measured or reported separately. When measurements have isolated foundation and dam seepage, the quantity of seepage penetrating the dam body has often been much smaller than the seepage from the foundation. Moler and Moore (1988) reported that of 15 CMC dams surveyed, only 3 had negligible seepage less than 1 ℓ/sec (10 gal/min). Seepage ranged from 1.2 L/sec to 38 L/sec (20 to 600 gal/min), including foundation seepage. No pattern was found, but seepage decreased with time. Hansen and Reinhardt (1991) and others have shown plots of unit seepage (seepage flow normalized by dividing by the average upstream dam face wetted area and by the average depth to the centroid of the wetted face) versus time for several RCC dams. The most significant feature of these plots is the steady reduction of seepage at all RCC dams with time. This consistent trend for both CMC and RCC dams is the result of healing of seepage routes by calcification, continued cement hydration, and perhaps by some siltation effects. More recent information indicates that RCC dams with minimal seepage have been constructed using a variety of upstream facing and lift joint treatment methods. These RCC dams have generally included some combination of seepage control elements, such as conventional concrete facing, partial lift bedding, and/or membranes embedded in precast panels. A consistent element in RCC dams with minimal seepage is the care applied in constructing the elements that prevent and control seepage in the dam. Geringer (1995) reported minimal seepage through several medium-height South African dams that used conventional concrete in the upstream face, partial bedding of the lift surfaces near the upstream face, workable RCC mixtures, and no membranes. Hansen and Reinhardt (1991) described the seepage performance of several RCC dams, including these conclusions: (1) “Initial seepage volumes from early lean RCC (low workability RCC) dams were in some cases more than anticipated.” (2) “Where measured seepage has increased significantly, it is usually due to leakage passing through a newly formed crack.” (3) “…Seepage is greater with increased head, with increased wetted surface area, and during cold weather when the RCC mass shrinks, thus creating greater crack widths.” (4) “Designs incorporating conventional concrete faces with water-stopped joints ... [or] membrane-faced precast panels have proved to provide a high level of watertightness.” The dam-foundation contact “is a prime potential seepage path and care must be taken to ensure [the contact] has a high degree of watertightness.” Dam seepage is ordinarily reported exiting the dam from such areas as the downstream face, from galleries, and from joints and cracks. Reports on a very few dams suggest foundation seepage entering the dam body through the foundation contact. The edge of RCC lifts tends to be less well compacted compared with the lift interior and tends to absorb more moisture from rain. This effect may result in the lift edges appearing damp, suggesting lift joint seepage instead of simple absorption of rainfall. The performance of some of the significant measures incorporated into RCC dams to control seepage are discussed below.

a. RCC mixture effects on seepage. The workability of the RCC mixture has played a significant role in seepage control, where more workable mixtures (Vebe times < 30 sec) have generally produced improved lift joint bond and watertightness. Some RCC dams constructed with less workable mixtures (Vebe times > 30 sec) (so-called lean RCC) have experienced seepage at the lift joints where segregation and/or incomplete compaction resulted in voids at the lift joint. Workable RCC mixtures can reduce compaction effort and improve compaction consistency, reducing overall permeability of the parent RCC. More significantly, workable mixtures have reduced segregation at the lift joint and have improved lift joint bond, resulting in lower permeability of the lift joint area and reduced seepage. The characteristics of workable RCC mixtures are discussed in Chapter 3, Mixture Proportioning, including Vebe time, sand content, NMSA, and cementitious materials type and content. At Monksville Dam, Hansen and Reinhardt (1991) reported that lower NMSA (from 75 to 50 mm (3 to 2 in.)) and increased sand content (40 percent) resulted in reduced segregation potential and reduced voids. Hansen and Reinhardt (1991) also reported at Arabie Dam that increased sand content (40 percent) assisted in reducing permeability of the RCC.

b. Special treatments and seepage.

(1) Conventional concrete facing. Most RCC dams with conventional concrete facing have had partial lift joint bedding as well. The seepage performance of these dams has been good, although somewhat variable, depending on the care taken during construction, and is likely the result of the lift joint bedding rather than the conventional concrete facing. Conventional concrete facing tends to crack at more frequent intervals than the RCC, due to drying and thermal shrinkage. Cracking of conventional concrete facing may occur as frequently as every 4.6 m (15 ft) and has occasionally initiated crack propagation into the body of the RCC, providing potential seepage paths into the RCC. Cracking of conventional concrete facing has been controlled successfully with contraction joints.

(2) Partial-width lift bedding mortar. This treatment for seepage control has been used on a number of RCC dams. Insufficient data have been reported to indicate how successful this has been, but many of these dams appear to have reasonably low unit seepage.

(3) Full-width lift bedding mortar. This has been used on only a few dams, with little reported seepage performance information available as yet because some of these dams are flood control structures with no permanent pool. Based on laboratory and test section studies, when used with workable RCC mixes, this treatment is expected to result in low rates of seepage.

c. Geomembranes. Upstream face membranes for RCC dams have generally consisted of PVC membranes integrally cast with precast concrete facing panels, with seams heat welded with PVC strips. Some reports of seepage penetrating these membranes suggest that welding of the seams was not completely successful. Urugua-I Dam (Lorenzo and Calivari 1992) experienced significant leakage through a face membrane system, and internal drains behind the membrane became a conduit for relatively substantial flow past the membrane. In addition, the connection of the membrane at the foundation interface has reportedly also led to significant seepage penetrating the membrane. More flexible formulations of PVC membranes have been used recently on at least one RCC dam. These membranes may offer some advantages over more rigid material formulations, depending on the environmental conditions the membrane is subjected to. At Galesville Dam (Hansen and Reinhardt 1991), a coal-tar-based elastomeric membrane was sprayed on the upstream face after cracking developed in the dam. The two 0.5-mm- (20-mil-) thick layers may have contributed to a reduction in overall seepage but could not bridge the existing cracks that penetrated the dam and did not stop leakage at those cracks.

d. Waterstops and drains.

(1) Waterstops. Waterstops have been relatively effective in controlling most leakage through contraction and construction joints, provided they were properly installed (in conventional concrete) and design details did not allow any means for leakage to bypass the waterstops. Where leakage has bypassed waterstops, it has often been due to either poor consolidation of the RCC/conventional concrete interface or cracking that developed around the waterstop. External waterstops placed over joints on the upstream face have been used, but were found to be expensive and subject to leakage when porous areas of concrete exist adjacent to the joint.

(2) Drains. Drains behind waterstops, or between double waterstops, have been successfully installed using cast-in-place techniques and by drilling after concrete construction using percussion drills. The drains have been generally terminated in a

gallery for seepage collection. Both vertical and angled drains through the dam body have been installed in some dams to assist in intercepting and draining any seepage paths through lift joints or cracks. No performance data are yet available to determine if such drainage systems are cost effective.

(3) Sealants. The use of joint sealant in dummy joints on the upstream face of dams has not been generally successful, possibly due to the use of improper sealants, improper application, and weathering of the sealant material. Sealants in general have a limited life, which would require maintenance and replacement at regular intervals during the life of the structure. This method of sealing joints should not be used for dams with permanent pools or where access for sealant replacement is limited.

e. Galleries. Galleries have helped perform several essential roles concerning seepage in all concrete dams, including the collection and measurement of seepage, instrumentation access, and internal observation of the dam structure. The methods of gallery construction in RCC dams have varied widely, resulting in gallery surfaces that range from very rough RCC to smooth cast-in-place or precast conventional concrete. In spite of the wide disparity in appearance, these galleries have performed their essential roles well. In galleries with very rough surfaces (that tend to diminish light), adequate lighting has sometimes been a problem. Where gutters have been omitted from galleries, control of seepage on gallery floors has caused safety and maintenance concerns.

8-3. Joints and Cracking

Cracking of mass concrete may occur in any dam, including RCC dams. Joints, material properties, and other design features are used to minimize or control volume change and consequent potential for cracking. Cracking in RCC dams has been generally similar to that seen in CMC dams. RCC dams have experienced more transverse cracking than CMC dams due to the use of very wide spacing between transverse joints or even the absence of transverse joints. CMC dams have closely spaced transverse construction joints that provide a fair degree of crack control. Longitudinal cracking has been a concern for large RCC and CMC dams, but this cracking has been controlled by reducing thermal contraction of the RCC by a variety of measures. Most cracking in CMC and RCC dams is due to thermal strains, induced as the concrete is cooling from the peak temperature rise, as discussed in Chapter 4, Properties. Cracking in conventional concrete facing for RCC is also affected by drying shrinkage. The spacing of cracks in RCC depends on a number of factors, including the coefficient of thermal expansion and the tensile strain capacity of the concrete. Widely spaced cracks may tend to have wider widths, while closer spaced cracks may have narrow widths. Wider cracks may have more potential for leakage. Cracking has also been caused partly by foundation or design conditions that result in locations of reduced dam section (such as transverse adits or spillway sections), abrupt foundation topographical changes, changes in foundation strength, abrupt dam section changes, or stress concentrations.

a. Transverse contraction joints. Most of the “lean” RCC dams constructed to date have had no transverse contraction joints. Many of these dams have had little significant cracking due to low thermal strain and, possibly, the high creep properties of RCC. Some of these dams have had seepage problems due to causes other than thermal cracking. Transverse contraction joints with upstream waterstops and joint drains have been effective in controlling cracking and leakage of CMC and RCC dams when the joint spacing has been small enough to preclude cracking between joints. Some leakage around waterstops has been reported when the waterstops in conventional concrete were not properly installed. When the spacing of transverse joints was too great, intermediate cracking and leakage have occurred. When installed in RCC dams, contraction joint spacing has varied from 15 to 40 m (50 to 130 ft) and, in some instances, over 90 m (300 ft). Typical joint openings reported have generally varied from 1 to 3 mm (0.04 to 0.12 in.). One instance of cracking due to misaligned transverse joints has been reported (Geringer 1995).

b. Thermal cracking. Thermal volume change has been the primary cause of significant cracking in RCC dams, as is the case with CMC dams. However, the construction joints typically used in CMC to facilitate placement are generally missing from RCC dams due to the abutment-to-abutment method of placement. Contraction joints have been one of the principal means of controlling thermal cracking in RCC dams, but designers have often used widely spaced joints to avoid potential interruption of RCC production and to reduce cost. In many RCC dams, these joints have been spaced too wide for actual construction conditions, and thermal cracking between the joints has developed. Actual placing temperatures have often been higher than considered in thermal studies, due primarily to construction delays pushing placement into warmer weather conditions than anticipated, but also due occasionally to unusual weather or materials problems. Often, thermal cracking has occurred months after construction and first filling of the reservoir, sometimes generating unusual spikes in seepage recordings. Like all concrete dams, the joints and cracks in RCC dams will tend to open with cooler weather and close with warmer weather. Where joints or cracks are widely spaced, these may open to a greater degree than conventional concrete dams with closer joint spacing. This has led to increased leakage in the winter months for some dams. At a number of RCC dams, little to no significant cracking has developed, particularly where relatively closely spaced joints were constructed. Where wider-spaced joints were used, cracks often formed at 30- to 35-m (100- to 120-ft) intervals, with a maximum interval of about 50 m (160 ft). Many of the "lean" RCC dams constructed have had little to no significant cracking, although some of these have had other problems with lift joint seepage. Cracking due to thermal shock has been experienced in RCC dams as in CMC dams. This has occurred when RCC placements were made during periods of moderate to high ambient temperatures followed by relatively sudden drops in temperature of 17 °C (30 °F) or more, rapidly cooling the surficial concrete and initiating surface cracking. These temperature changes have generally occurred unexpectedly, when insulation blankets or other protective measures were not available. A few significant cases of cracking have been described in the literature:

(1) Copperfield Dam (Hansen and Reinhardt 1991) - A transverse crack through the spillway section of the dam occurred 7 months after initial filling.

(2) Upper Stillwater (Hansen and Reinhardt 1991, Richardson 1992) - Transverse thermal cracking was expected in this long structure, and a number of cracks developed, several of which were significant and required treatment due to heavy leakage.

(3) Galesville Dam (Hansen and Reinhardt 1991) - Seven significant transverse thermal cracks occurred through the dam, requiring treatment to reduce seepage.

c. Foundation-related cracking. Foundation terrain or displacements can initiate or affect cracking in any concrete structure or dam. A few RCC dams have had small foundation downstream or vertical displacements upon first filling of the reservoir, some of which may have contributed to cracking in the dam. RCC dams with widely spaced transverse contraction joints may be slightly more prone to foundation-related cracking, lacking more closely spaced joints that can provide strain relief. Foundation terrain, particularly where significant changes in slope exist, have caused designers to locate joints at locations of potential stress/strain concentration. These joints appear to have been mostly effective. A few RCC dams have cracked at changes in dam section such as at gallery locations or where the foundation slope changed. At Upper Stillwater Dam, 10 mm (0.4 in.) of downstream foundation movement was measured after filling, with no movement in the dam detected (Richardson 1992, Hansen and Reinhardt 1991). No further movement has been reported. This may have initiated a significant transverse crack that required later treatment for leakage.

8-4. Durability

The primary durability concerns for RCC dams are resistance to abrasion-erosion of flowing water and freezing and thawing.

a. Abrasion-erosion. The abrasion-erosion resistance parameters for RCC are similar to those for CMC. Concrete surfaces subjected to flow velocity over 12 m/sec (40 ft/sec) should be protected as required in EM 1110-2-2000. Due to the still relatively short performance history of RCC dams, comparatively few have sustained major flows. None have yet been reported as being subjected to high-velocity flows. Some large-scale high-velocity flow tests have been run on RCC at the Detroit Dam Test Flume (Schrader and Stefanakos 1995) at velocities reported ranging from 22 to 32 m/sec (72 to 105 ft/sec) for variable exposure durations. Much of the abrasion-erosion performance of RCC structures is observational in nature (Hansen and Reinhardt 1991, Schrader and Stefanakos 1995). A wide variety of RCC dams and overtopping protection structures have been overtopped with low to moderate velocity flows and have performed well. Some of these have been overtopped during construction, sustaining little damage. Few of these events have flow velocities reported. A number of RCC dams have exposed RCC spillways where relatively high velocity flows are expected, but only for rare events. A few cases of interest are described in the literature:

(1) Tarbella Dam (Lowe 1988) - RCC protection in several applications at the outlet works and downstream performed well under moderate velocity flows.

(2) Kerrville Ponding Dam (McDonald and Curtis 1997) - RCC performed well with minor loss of surface at about 4-m/sec (14-ft/sec) sustained flow velocity, with subsequent overtoppings also causing minimal damage.

(3) Toutle River (McDonald and Curtis 1997) - An RCC spillway for a volcanic debris retaining dam was subjected to sustained severe debris overflows at estimated velocities up to 6.1 m/sec (20 ft/sec), resulting in moderate abrasion-erosion damage. The volcanic sediments ranged up to 0.6 m (2 ft) in size.

b. Freezing and thawing. Although several RCC dams have been constructed in freezing and thawing areas, the RCC has generally been protected by conventional air-entrained concrete surfaces. A few dams have had sacrificial sections of RCC constructed to protect the interior RCC. Little information is yet available concerning the performance of RCC in freezing and thawing areas. Hansen (Hansen and Reinhardt 1991, Liu and Tatro 1995) reported that both Willow Creek and Galesville Dams have exposed RCC sections in moderate freezing and thawing regions and that minimal freezing and thawing damage had occurred to date. Hopman (1992) reported some shallow freezing and thawing damage on the crest of the unfinished Elk Creek Dam where rainwater had ponded and saturated the surface. Dam crests that are adequately sloped or crowned to avoid ponding of water on the surface have been less subject to freezing and thawing damage. Recent RCC dams that have included some air entrainment in the RCC have not had enough exposure time to evaluate the effectiveness of the air entrainment. A significant number of RCC pavements (RCCP) have been constructed in freezing and thawing areas, particularly in Canada and the United States. Entraining air in the very unworkable RCC mixtures used in RCCP has not been possible, so none of these pavements have entrained air for freezing and thawing protection. In spite of this, the majority of these pavements are in good condition after several years of often frequent cycles of freezing and thawing. This appears to be due at least partly to the relatively high strength of most RCCP. The freeze thaw damage usually found in these pavements is spalling and raveling at the cold vertical construction joints and some minor loss of surface. On some dams where the downstream face of RCC has been left exposed, either in steps or on a simple slope, the loose debris remaining from RCC placement at the face has been removed by air blast or other means. Removal of this debris encourages surface runoff and discourages plant growth, allowing observation of any deterioration, reducing safety concerns, and reducing damage due to freezing and thawing.

8-5. Chemical Effects

a. Calcium carbonate. Calcium carbonate precipitation is a common and, generally, minor problem with all concrete dams. The effects of this precipitate have often been beneficial in terms of long-term seepage reduction. Calcium hydroxide is released from the cement hydration and is carried by seepage to a surface where it reacts with the carbon dioxide in air and forms a precipitate, described in the formula:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

The formation of this white precipitate or similar reactions is commonly called efflorescence or calcification. Other minerals may alter the color of this precipitate. Calcification tends to heal areas of seepage with time by filling the areas with calcium carbonate, but this may also clog foundation or dam drains and create slippery conditions in galleries and undesirable changes in downstream water pH levels. The clogging of drains often necessitates the cleaning or reaming of drains on a recurring basis. The amount of calcium hydroxide available for reaction diminishes with time, although precipitation in some dams may continue for many years. This is due to the fact that there is a fixed amount of soluble lime free for precipitation in concrete and diminishing seepage will tend to transport diminishing amounts of calcium hydroxide. RCC structures may be slightly less susceptible to calcium carbonate precipitation, due to the slightly lower cementitious materials content of RCC compared with CMC and to the common use in RCC of significant amounts of pozzolan. All pozzolans will react with and tie up significant amounts of the soluble calcium components from cement hydration. This will vary with the cement used, the pozzolan used, and the mixture proportions. For relatively dry RCC mixtures, significant unhydrated cement may produce more calcification than expected. Some reports have indicated calcium-carbonate-laden dam seepage changing the pH in the water downstream of the dam (Hansen and Reinhardt 1991). In one case, the dam seepage was collected and pumped back into the reservoir to reduce the effect downstream. In another, the cracks and joints were repaired to reduce seepage and correspondingly the pH effect in downstream waters. Hansen and Reinhardt (1991) reported higher pH of seepage through slower flowing cracks compared with more rapidly flowing cracks at Copperfield Dam, suggesting that water passing more quickly through concrete may have less opportunity to dissolve available calcium hydroxide than water slowly seeping through the concrete. Higher porosity in portions of a concrete mass may also result in greater calcium carbonate deposition due to the ready availability of a larger concrete surface area to seepage.

b. Hydrogen sulfide. Hydrogen sulfide generation can be a problem in both CMC and RCC structures, depending on water and temperature conditions. Under certain anaerobic water conditions, hydrogen sulfide gas may be generated in reservoirs and dam outlet works, producing a dilute sulfuric acid. This dilute acid can attack and slowly deteriorate the surface of concrete. The effect is often a softened paste appearance on the concrete surface and a slow loss of surface concrete. Hansen and Reinhardt (1991) described this effect at Willow Creek Dam.

c. Other chemical effects. Very aggressive reservoir water that contains unusual chemical constituents can produce acid attack on concrete or unusual precipitates upon contact with concrete. Mineral-free waters (ACI 201.2R) can produce leaching of concrete components. These effects have been observed at least two RCC dams, and in one case the seepage stained the concrete black within days of first appearing on the downstream face. Concerns regarding aggressive water at Willow Creek Dam in the 1980s resulted in a comprehensive investigation that concluded that no deterioration due to aggressive water had occurred to date (Liu and Tatro 1995). There have been no reports to date of any alkali-aggregate reactivity or sulfate attack in any RCC structures.